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ABSTRACT

The need to make manufacturing, operation, and support of airborne vehicles safer and more efficient forces engineers and scientists to look for lighter, cheaper, more reliable technologies. Light weight, immunity to EMI, fire safety, high bandwidth, and high signal fidelity have already made photonics in general and fiber optics in particular an extremely attractive medium for communication purposes. With the fiber optics serving as a central nervous system of the vehicle, generation, detection, and processing of the signal occurs at the peripherals that include smart structures and devices.

Due to their interdisciplinary nature, photonic technologies cover such diverse areas as optical sensors and actuators, embedded and distributed sensors, sensing schemes and architectures, harnesses and connectors, signal processing and algorithms. The paper includes a brief description of work in the photonic area that is going on at NASA, especially at the Glenn Research Center (GRC).

Keywords: Fiber optics, photonics, sensing, actuation, smart systems, signal processing, vehicle health management

1. INTRODUCTION

Use of optical technology on aerospace vehicles has been attracting scientists and engineers for years. Many of them saw an advantage in the replacement of traditional electrical wires with optical fibers. The replacement, they argued, would result in lighter and safer systems. Lower weight, immunity to EMI, and high signal fidelity were the main arguments that accompanied the introduction of such NASA and DOD programs as Fiber Optic Control Sensors Integration (FOCSI), Fly-by-Light / Power-by-Wire (FBL/PBW), and others.[1-4] These programs ended with successful demonstrations of photonic technologies and showed the feasibility of the using optical cables, sensors and interfaces on military and commercial aircraft. However, the early successes revealed problems that formed a barrier to further implementation of photonic technologies. A high cost of individual components and harsh environment these components were subjected to are just some of them.

Fiber optics has also found its way into aircraft avionics as a medium for high data rate communication bus. Security of communications, high signal fidelity, and its ability to move around large blocks of information with a significant speed helped the 20 Mbit/sec 1773 bus to become a backbone of modern aircraft communication system. The photonic technology developed in response to requirements from the telecommunication industry has produced a number of new components and system configurations such as fiber optic Bragg gratings, vertical cavity surface emitting diodes (VCSEL), and dense wavelength division multiplexing (DWDM).

Meanwhile, a business pressure has forced the aerospace industry to look for new ways to increase productivity and reduce operational cost without sacrificing safety of the public on the ground, passengers, and the crew. The aircraft industry in an attempt to cut costs looked into new ways to reduce the downtime and to streamline the process of identifying and replacing faulty parts and components. As a result, there has been an increased advocacy for aircraft maintenance on demand rather than by schedule. In the reusable launch and space transportation vehicle areas, a battle for each pound of useful payload has led to introduction of such technologies as MEMS, smart structures, nano-systems and photonics.[5, 6] The safety issues related to possible sparking and short circuits also attracted attention to optical fibers as a possible replacement for electrical wires.

Thus, a necessity to reduce weight and enhance safety of the vehicle coupled with recent advances of communication technology, allowed photonics to pose itself as a technology that could respond to requirements of the aerospace industry.

This paper identifies and reviews photonic technologies that either are becoming part of or are competing with existing technologies to be used in smart systems and structures. A special emphasis is made on the challenges these technologies face. In describing photonic technologies a distinction will be made between those that are on a relatively high technology readiness level and emerging technologies. This paper also describes major vehicle systems that will benefit from using photonics.

2. IMPLEMENTATION OF PHOTONIC TECHNOLOGIES

Introduction of optical fibers as a principal medium for transmitting information on an aerospace vehicle has brought benefits of lower weight and enhanced safety. Also it brought a capability to communicate rapidly between various peripheral devices and move around large blocks of information at a high speed. Thus, benefits of using photonics are the most visible at a system level. The implementation of photonic technologies, however, may be introduced on every level including components, signal processing, interfacing, system integration, and testing. Each of the levels requires its own technology development.

2.1. Sensors and Actuators

Smart systems incorporate sensors, actuators, power converters, interfaces, signal processing elements, and other components that together provide functions necessary for assessing the flight and safety environment and generating the most favorable response to meet the mission objectives. Various types of sensors and sensing schemes have been developed over the past decade. Descriptions of their specific configurations and principles of operations may be found elsewhere.[7, 8] Among a great variety of sensors, those that operate in the wavelength domain are especially attractive because of their inherent multiplexing capabilities. The feasibility of using fiber optic Bragg gratings and Fabry-Perot interferometers in aerospace applications has been demonstrated.[9, 10]

Actuation plays a special role in any active system as a power conversion element. In aerospace applications the incoming electrical or hydraulic power is, in most cases, converted to mechanical power. Piezo-electric elements are examples of conversion of applied electrical power to vibrational energy.[11] In a smart system the end result or reaction of the system to the environment would be to change shape, position, or material properties of the corresponding component. Piezoelectrically driven actuators for aircraft applications have already been demonstrated and reported.[12]

Similarly, the profile of a surface may also be altered photonically.[13–16] One of mechanisms to photonically induce surface deformation is based on stresses and strains generated in photosensitive materials by an interferometric pattern. The mechanism is described in Fig 1. Two beams interfere and form a periodic change in the refractive index in a film of a photorefractive material. The changes in the refractive index are accompanied by periodic changes in material strain and result in periodic deformations on the surface of the material (See Fig. 1a). A probe beam was used to detect these optically generated surface corrugations. The periodic corrugations with amplitude of 6nm were observed and detected (Figs. 1b and 1c). Proper selection of material would permit design and construction of a component with surface deformations controllable by the optical interferometric pattern.

2.2. Signal Processing

In photonic sensing systems the journey of an optical signal ends at the surface of a photodetector, where the optical signal is converted to an electrical one. Most photodetectors are square law detectors and are sensitive to a total amount of power that falls on their surfaces. Thus, it is important in sensing systems operating in the wavelength domain to have a device capable of reading the wavelength. Two wavelength reading techniques are being developed at the NASA Glenn Research Center. Both techniques are interferometric in nature. The first one is based on a wavelength to RF conversion. It employs an equal path interferometer, projector, and a focal plane array (CCD). The schematic of the experimental setup is shown in Fig. 2a.

Two optical sources are used simultaneously, a light emitting diode (LED) with the central wavelength of 820 nm and a HeNe laser. Figures 2b and 2c show signals from the CCD. The signals overlap in the time domain (Fig. 2b) and a less coherent light source, the LED, produces a more narrow wavelet. In the frequency domain the signals are separated. The separation of signals in the frequency domain is clearly seen on a screen of an electronic spectrum analyzer (Fig. 2c). The signal belonging to a light source with a shorter wavelength, the HeNe laser, is represented in the frequency domain by a peak at a higher frequency. Because of a longer coherence length of the light emitted from the HeNe laser this peak has a significantly narrower bandwidth than the other one that belongs to the LED.

The second wavelength demodulation technique involves a conventional unbalanced interferometer. The unbalance permits processing rapid changes in the wavelength light. To achieve the best performance the interferometer should be properly designed and have an appropriate unbalance. The principle of operation of the signal processing unit used is shown in Fig. 3a. For the wavelength of 1300 nm and the full-width at half-power bandwidth (FWHP) of 0.3 nm the optimum optical path length unbalance was computed to be about 2.1 mm. Fig. 3b shows dependence of the interferometer sensitivity on the interferometer optical path difference (unbalance). The curve has a maximum value that is due to the finite coherence length of the optical signal reflected back by the grating.

2.3. Interfaces

Interfacing of photonic components has several forms. One of the best known forms of interfacing is an electro-optic interface which permits coupling of light from a laser or LED into optical fiber. Another form of interfacing is an optical connector. To minimize the number of fiber-to-fiber connectors a connectorless junction technology is being developed by the Glenn Research Center. The technology is based on an optical beam self-trapping in photosensitive polymers with light induced modifications of the refractive index.[17–19] The principle is demonstrated in Fig. 4. A small amount of photosensitive polymer gel is placed between two ends of optical fibers that have to be connected. Light is sent into the other two ends. The wavelength of the entering light is within the spectral absorption band of the gel. The light helps the gel to solidify or to cure. At the same time some light is being absorbed by the gel and in the process of absorption the refractive index of the gel changes. If the refractive index decreases with absorption a channel would be formed similar to a waveguide. The waveguide would also become an optical concentrator preventing the light from dispersing. Thus, by sending light from opposite ends of fibers two waveguide like channels are formed that act as a bridge between two fibers. After a curing process is complete a permanent channel is formed connecting the two fibers. The channel is then used to propagate optical signals between the two fibers at operating wavelengths.

3. SYSTEMS WITH PHOTONIC ELEMENTS

Integration is one of the biggest issues that photonic technologies face.[20, 21] With a rapid technological progress in MEMS and wireless communication technologies, significant benefits may be obtained by combining these technologies with photonics. Optical and optically powered MEMS, wirelessly excited and powered components, and other hybrid systems may provide the maximum benefits.

3.1. Embedding of Sensors in High Temperature Polymer Matrix Composites

Packaging and embedding techniques represent another issue. At the GRC commercially available high temperature Bragg gratings have been embedded in about 3 mm thick plates made of polymer matrix composite (PMC) materials. Information about some high temperature polymer matrix composites developed at the Center may be found in Ref. 22.

The process used to embed fiber optic Bragg gratings in PMC involves several steps. During the first step a mold is prepared using a commercially supplied prepreg consisting of graphite fiber fabric and polyimide thermoset resin cut and placed together into a steel tool. In the mold, the prepreg is symmetrically placed between the following processing aids: non-porous Teflon® peel ply, 2 layers of E-glass, and porous Teflon® peel ply. The non-porous plies are placed on the outside (mold-side) of the ply lay-up. The porous peel plies sandwich the prepreg. Finally, an about 6 mm thick steel plate is placed on top of the nonporous peel ply and the 8 plies of prepreg.

All plies of the prepreg are warped aligned in the mold, on top of a vacuum plate, with the fiber optic placed in the center of the 8-ply stack. The fiber optic is protected from the steel mold closures so that a signal is continuously monitored throughout the processing trial. The mold is covered in a large sheet 2 mil Kapton® and secured with a metal frame to ensure a vacuum during processing.

The steel mold containing the 8 plies of prepreg and the fiber optic are placed in a hydraulic press at room temperature. Stops are inserted between the press platens to prevent excessive resin flow during the initial heating stages of the processing cycle. Vacuum (6" Hg) is applied to the mold and the Kapton® quickly conforms to the 6 mm thick tool containing the prepreg. The press is heated at 5°F/minute until the mold temperature reaches 300°F (about 149°C), then the vacuum is increased to 25" Hg. After that the press is heated up more at the ramp rate of 2°F/minute until the mold temperature reaches 450°F (about 232°C) and maintained at that temperature for 60 minutes. After the 60-minute hold at 450°F, pressure of 200 psi is applied to the mold and the mold temperature is ramped up again to 600°F (about 310°C) at the same ramp rate of 2°F/minute. The mold is than held at 600°F for 120 minutes and then cooled to 400°F (about 204°C) over three hours. The process is described in Fig. 5. During this molding cycle, data from the embedded fiber optic Bragg grating was recorded using a optical spectrum analyzer. A picture of the PMC panel with an embedded fiber optic Bragg grating is shown in the lower right corner of the Figure. Fiber optic pigtails are clearly visible. The upper part of the Figure displays also recorded images of an optical spectrum analyzer's screen. The images depict positions of spectrally encoded signals reflected by the embedded grating at two temperatures, room temperature and 600°F.

The gratings survived the embedding process as well as numerous subsequent thermal cyclings from room temperature to 300°C. However, during the process of thermal cycling a hysteresis was observed. It presence was attributed to the fact that the commercially available fiber was initially annealed at 300°C. An additional annealing and holding the fiber with the grating at 420°C for 24 hours resulted in a somewhat smaller hysteresis. Fig. 6 shows results of thermal tests of a stand alone fiber with a grating.

3.2. Fiber Interfacing and Connectorization

Components or panels with embedded fiber optic sensors would have fiber optic pigtails. A presence of the pigtails would make manufacturing, transportation, and integration of components or panels very difficult. In addition to the fiber pigtails being fragile, the real challenge would be to interconnect two panels, for instance, with fibers sticking out. Introduction of novel photonic interfacing techniques shown in Fig. 7 may minimize these problems. Free space optical connectors (Fig. 7a) are based on a simple concept of transmission of optical signals using bulk optics devices. A free space optical connector consists of a set of two micro-optical assemblies. Each assembly is connected to a mating end of an optical fiber and buried into components of a structure along with the fibers. When the components are assembled the two micro-optical assemblies form one unit with a continuous transmission of signal from one fiber to another. This approach may be applicable in a relatively clean environment in systems that can tolerate significant variations in the signal levels.

Fig. 7c describes a hybrid interfacing technique that permits communicating through a wall. The technique may be applicable for both embedded and surface mounted photonic systems. It is based on converting optical signals into electromagnetic signals at, for instance, radio frequencies. The electromagnetic signals propagate through the wall and are converted to the optical ones on the other side of it.

The last two techniques use a phenomenon of forming waveguide like channels in photorefractive materials as described above in Section 2.3. The first of them (Fig. 7b) permits across the seam interfacing of several embedded fibers. The other one (Fig. 7d) enables splicing of a single fiber or ribbon cable without using mechanical connectors.

3.3. Vehicle Health Management

Integrated vehicle health management (IVHM) is a complex of measures that gives the piloting crew and repair crew on the ground the advance knowledge about the health conditions of various components, subsystems, and structures of the vehicle. Also, IVHM provides information to control units about environmental and flight conditions necessary for accomplishing safety and mission goals.

Photonic vehicle health management techniques that are being developed could be either passive or active. One passive technique consists of a web of optical fibers that covers a structure of interest or a portion of it. Optical strain sensors attached to the fibers detect slow varying changes in strain distribution in the structure. A signal processing algorithm determines if these changes are associated with structural changes.

In an active approach, the web of fibers is replaced by a fewer number of fibers with sensors. An actuation unit is added to provide an acoustical excitation of a structure. The active approach does not have to have a separate actuation unit. In some applications the acoustical excitation may be generated by a component itself. For instance, conditions of a pump may be evaluated by monitoring the acoustic emission from the pump. Some techniques to detect acoustic emission using fiber optic sensors have been described in the literature.[23]

Figure 8 shows schematically all three cases described above. The first case depicted in Fig. 8a has a curved panel instrumented with a web of embedded fibers with passive Bragg gratings. In Fig 8b the web of fibers is replaced by a fewer number of sensors and an actuator is added. The actuator generates an acoustical signal that propagates through the structure and reaches the sensors. Any changes in the structure would change the signature of the signal picked up by the sensors.

The last figure, Fig 8c, shows a fiber optic Bragg grating attached to the casing of a pump. A set of acoustical signatures of a pump properly operating at different flight and environmental regimes is stored in a computer memory bank. During the flight, the acoustical signal emitted by the pump is detected by an optical sensor, then compared with the corresponding one from the bank, and discrepancies are recorded. In case the discrepancies exceed tolerances an advanced warning would be given to the flight control unit, flight crew, or the ground maintenance crew.

To demonstrate performance of an active health monitoring system a piezo-electric actuator is mounted on a surface of a panel made of polymer matrix composite material with fiber optic Bragg grating imbedded in it. The grating responds to acoustical waves in the plate generated by the vibrating piezo-electric actuator and modulates the wavelength of light that reflects from it. The optical signal is sent to a wavelength detection unit that employs an unbalanced interferometer described in section 2.2. of this paper. The schematic of the experimental system is shown in Fig. 9. The figure also displays the signals associated with actuation and detection of periodic perturbations at 1 KHz.

4. SUMMARY

Introduction of photonic elements into smart systems offers numerous benefits. In addition to reducing weight and enhancing safety it also opens new technological opportunities. Availability of components that change their shape in response to light of a certain wavelength and have ability to generate and control corrugations on the surface of components using photons would permit development of optically based smart structures and systems. Devices built on these phenomena could be employed in such applications as, for instance, fuel and air injectors whose nozzle geometry is controlled by light. Boundary layer controllers that use interactions of the air flow with optically driven and controlled surface corrugations represent another application of photonic technology to smart aerospace systems.

Advanced signal processing devices and schemes that possess simultaneously high sensitivity and broad bandwidth would detect transients and therefore be used for damage detection and evaluation. Their applications could also be extended into such areas as detection of pulsed pressures. In compressors, circumferential pressure waves are indicators of a stall. They occur at frequencies characteristic for a given compressor.[24] Early detection of these waves at given frequencies using fiber optic sensors located along the inner circumference of the compressor casing would give an early warning about stall conditions.

Optical fibers coated with photorefractive materials capable of forming light guiding channels in themselves open new opportunities in how fiber optic cables are repaired. The material would penetrate into areas where cracks in the fiber occur and after exposure to light at a certain wavelength form a permanent channel. Such a smart self-repairing optical fiber would require a minimal human interference and increase significantly safety and reliability of airborne photonic systems.

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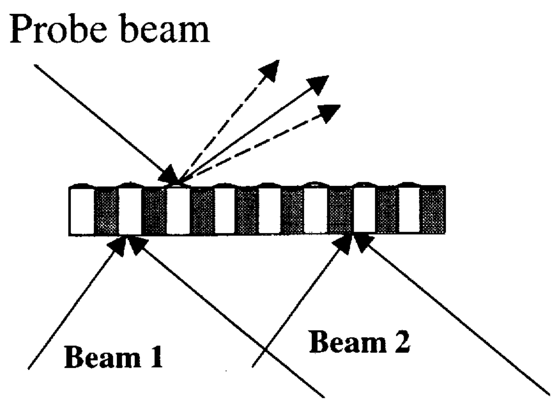

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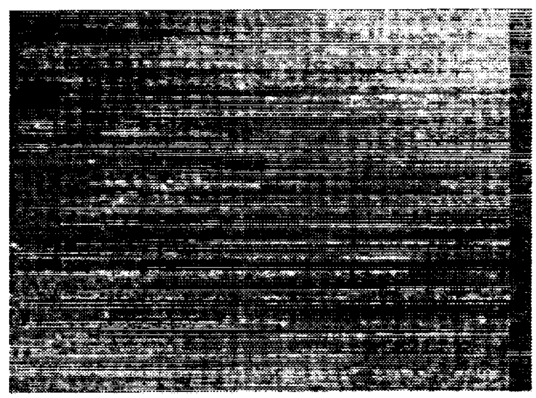

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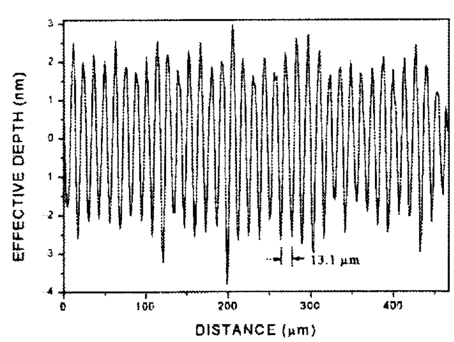

Fig. 1. Optical actuation:

a) Schematic of the two beam mixing with the probe beam;
b) Picture taken with a WYKO 2000 interferometer showing periodic surface corrugations with about 6 nm peak-to-peak amplitude;
c) The data after Fast Fourier Transform of the raw data.

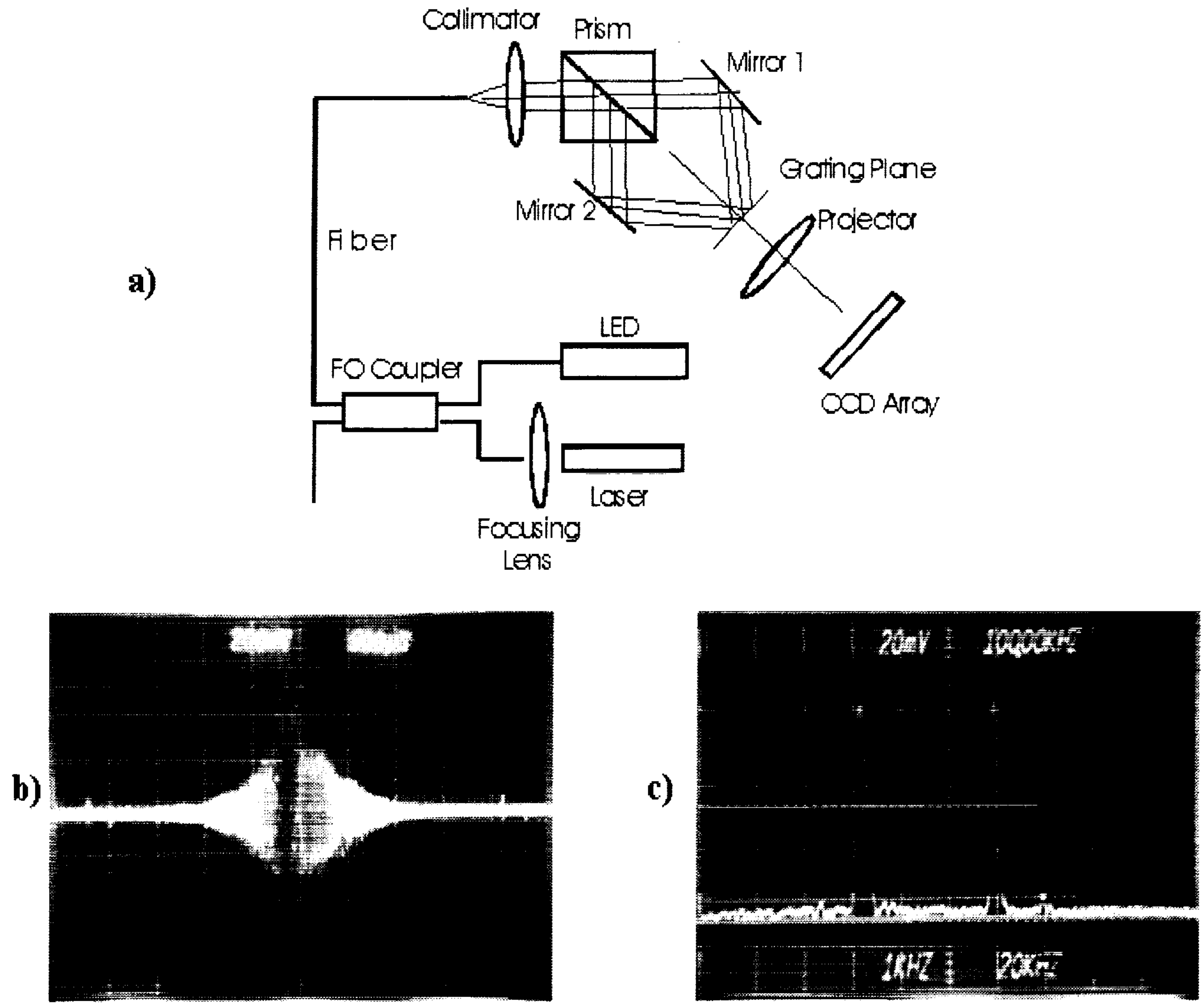

Fig. 2. Signal processing scheme involving wavelength-to-RF conversion:

a) Schematic of experimental setup with two simultaneous light sources, HeNe laser (wavelength λ = 632 nm) and light emitting diode LED (central wavelength λ = 820 nm);

b) Signals from the CCD array displayed in the time domain on the screen of oscilloscope (a more narrow wavelet belongs to a less coherent light source, the LED);

c) Signals from the CCD array displayed in the frequency domain on the screen of a spectrum analyzer (a peak at a higher frequency belongs to a light source with a shorter wavelength λ, the HeNe laser).

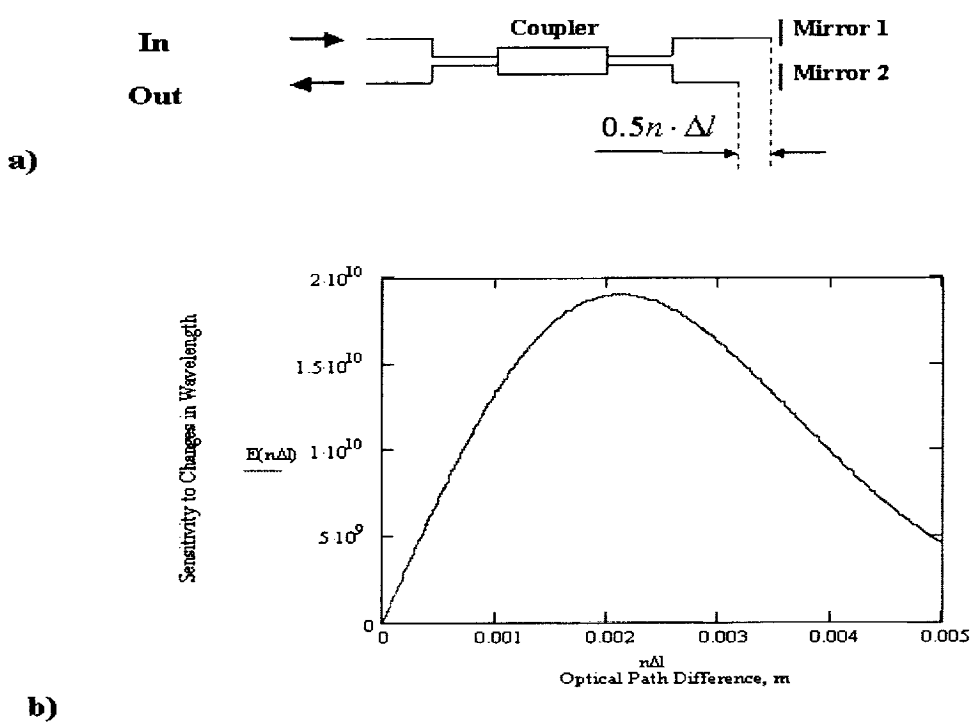

Fig. 3. Processing of dynamic signals using unbalanced interferometer:

a) Schematic drawing of the interferometer;
b) Dependence of sensitivity to dynamic changes in wavelength on optical path difference of the interferometer.

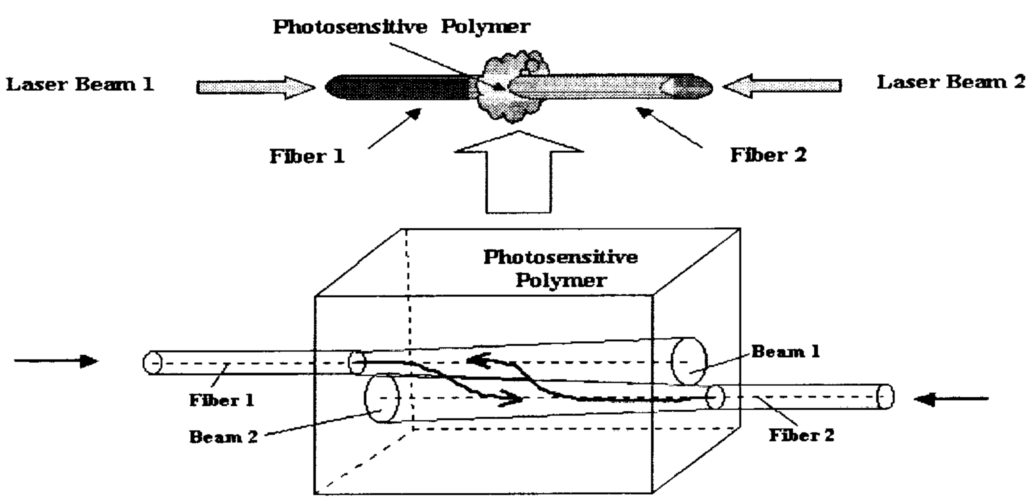

Fig. 4. Schematic explanation of a connectorization process of two fibers using a phenomenon of a laser beam self trapping in photosensitive polymers.

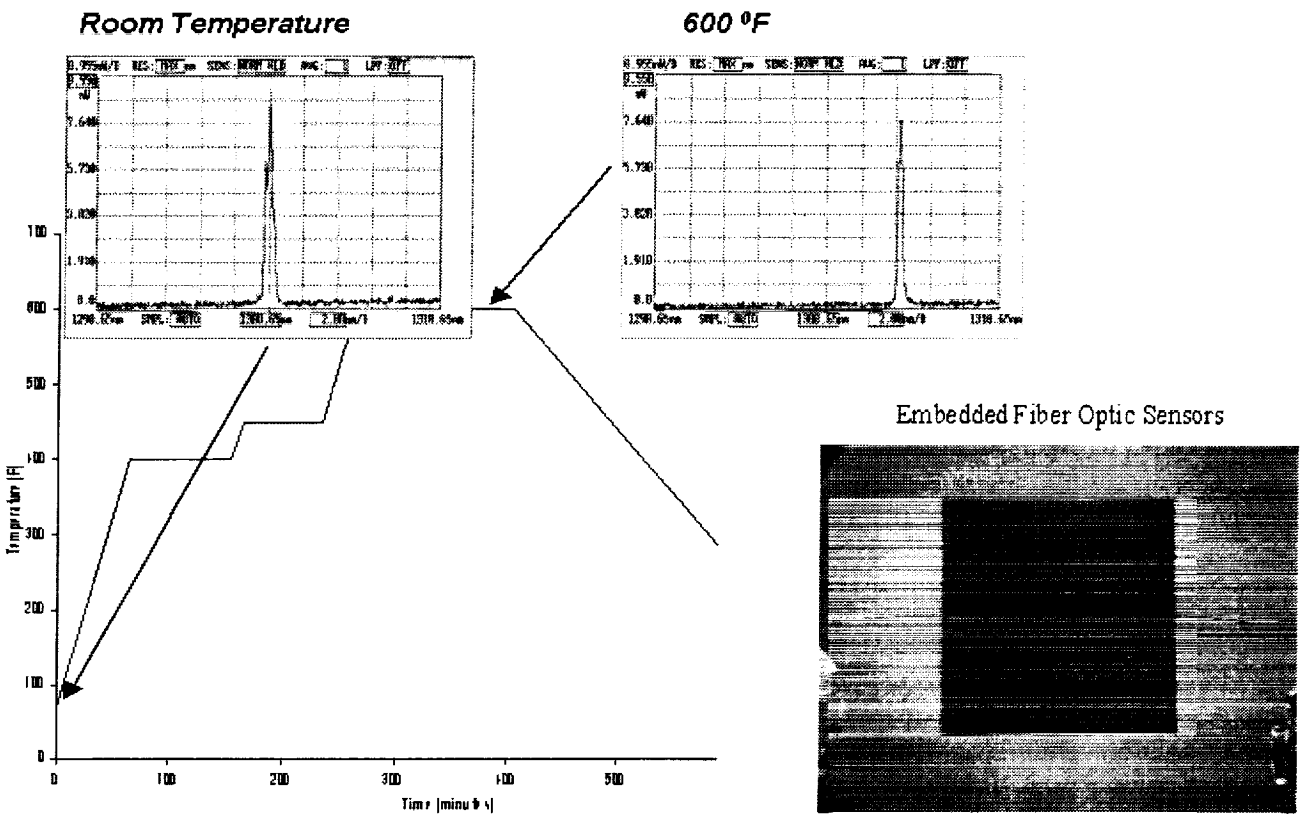

Fig. 5. Fiber optic Bragg grating embedded in high temperature polyamide matrix composite plate.

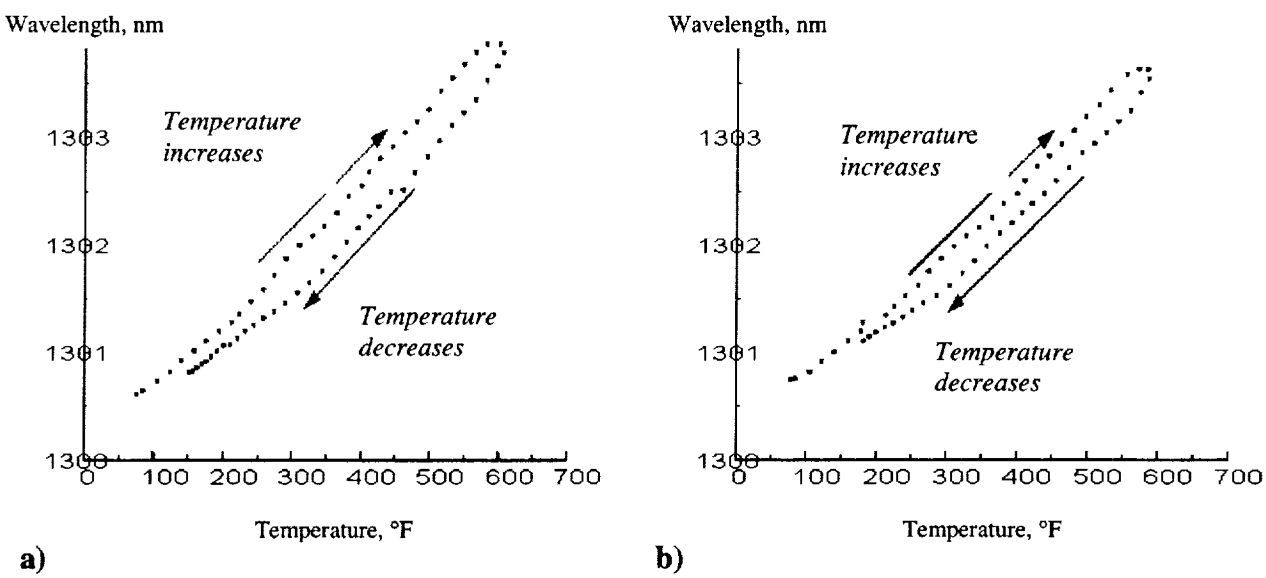

Fig. 6. Results of thermal tests of a high temperature fiber with FOBG (averaged over 3 runs):

a) Commercial fiber with FOBG annealed at 300°C;
b) Fiber with FOBG re-annealed at 420°C for 24 hours.

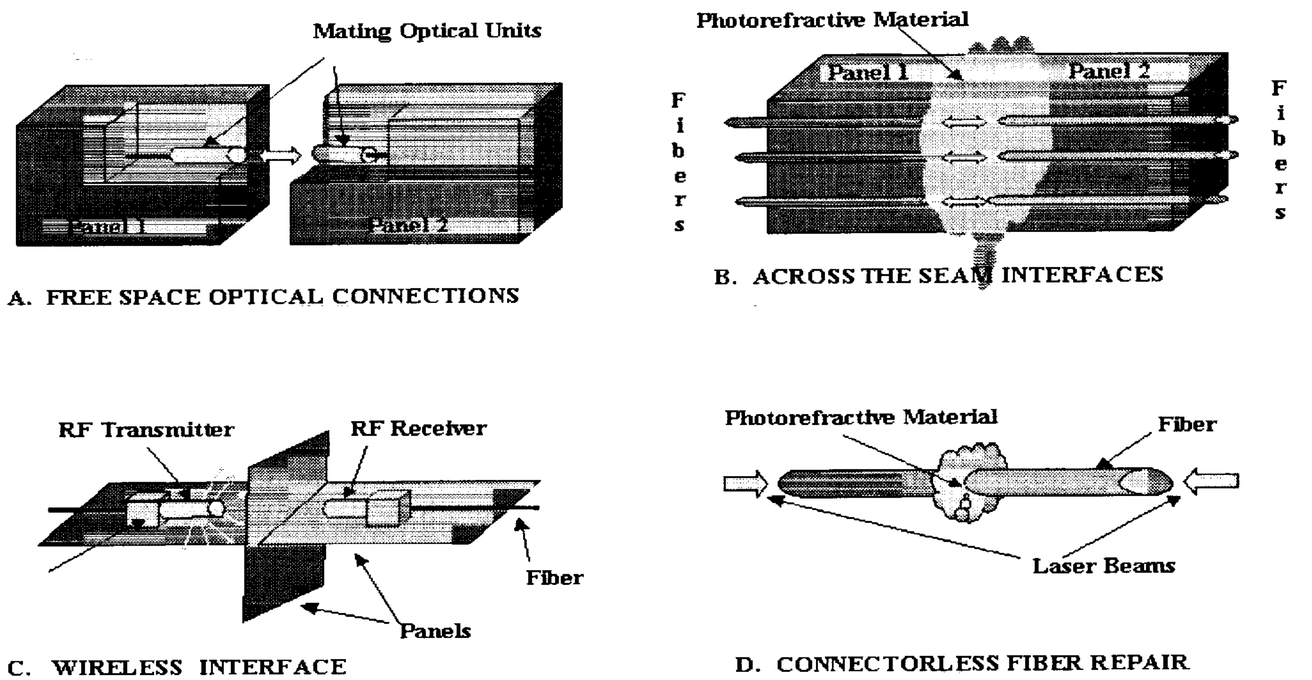

Fig. 7. Examples of novel photonic interfacing technologies:
A) Free space optical connections; B) Across the seam interfaces;
C) Wireless interface; D) Connectorless fiber joint.

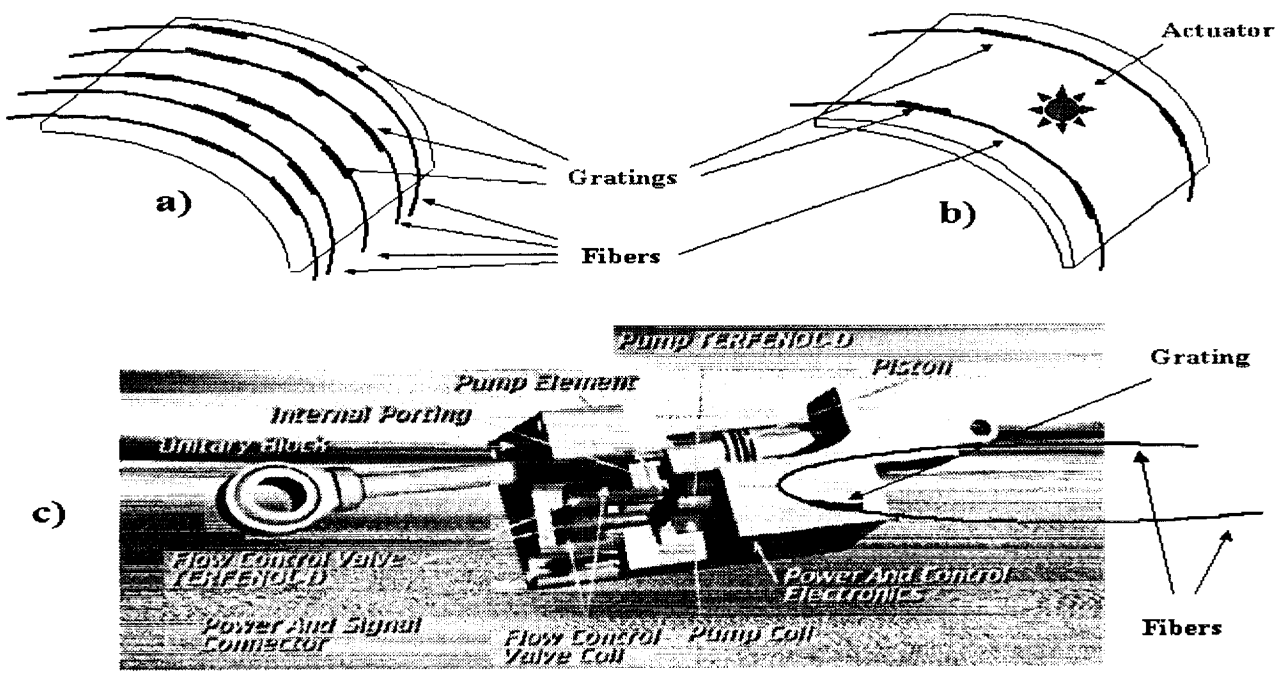

Fig. 8. Vehicle health management schemes:
a) Passive health management system; b) Active health management system;
c) Dynamic health management system (TERFENOL-D® is a trademark of ETREMA Products, Inc.).

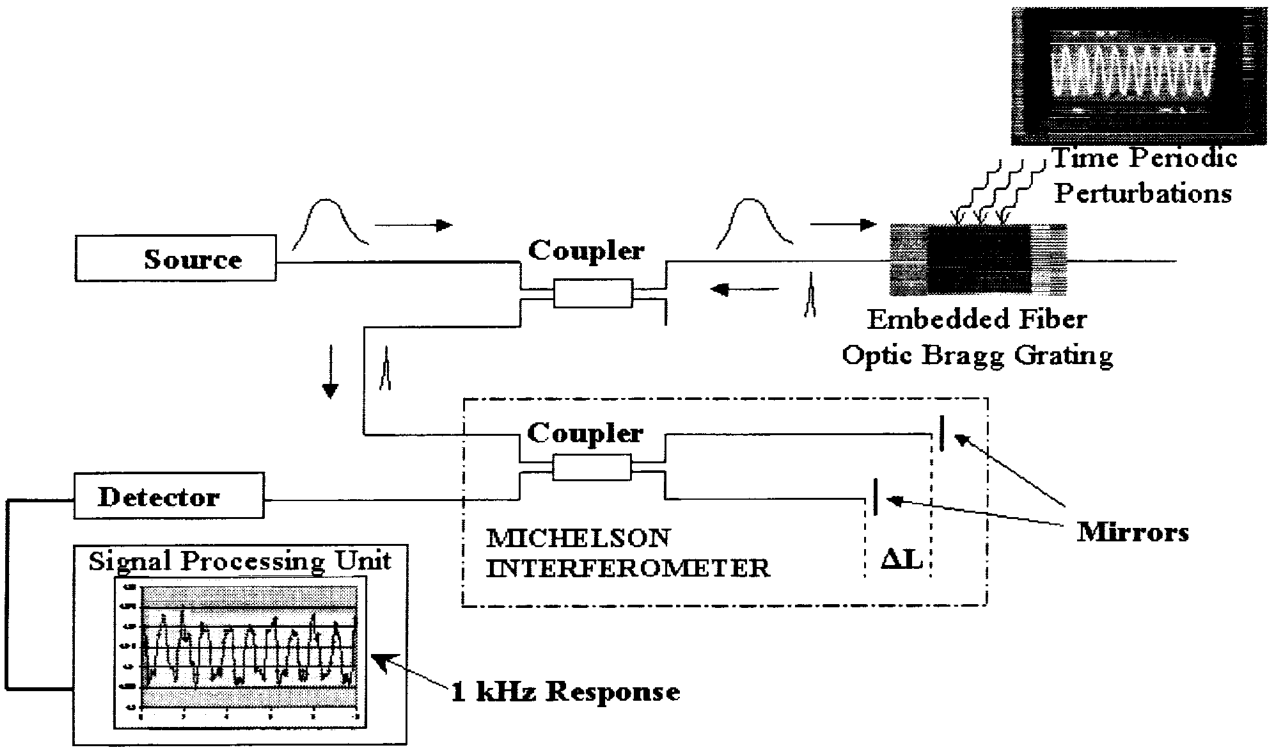

Fig. 9. Bragg grating based fiber optic sensing system for measurements of periodic perturbations.

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13. ABSTRACT ***(Maximum 200 words)***

The need to make manufacturing, operation, and support of airborne vehicles safer and more efficient forces engineers and scientists to look for lighter, cheaper, more reliable technologies. Light weight, immunity to EMI, fire safety, high bandwidth, and high signal fidelity have already made photonics in general and fiber optics in particular an extremely attractive medium for communication purposes. With the fiber optics serving as a central nervous system of the vehicle, generation, detection, and processing of the signal occurs at the peripherals that include smart structures and devices. Due to their interdisciplinary nature, photonic technologies cover such diverse areas as optical sensors and actuators, embedded and distributed sensors, sensing schemes and architectures, harnesses and connectors, signal processing and algorithms. The paper includes a brief description of work in the photonic area that is going on at NASA, especially at the Glenn Research Center (GRC).

14. SUBJECT TERMS

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